Impact of magnetic topology on radial electric field profile and comparisons with models of edge transport in the Large Helical Device

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PACS number: 52.55.Hc, 52.55.-s, 52.30.Cv, 52.30.-q, 52.25.Fi

Abstract. The radial electric field at the plasma edge is studied in the Large Helical Device (LHD) experiments. When magnetic field lines become stochastic or open at the plasma edge and connected to the vessel, electrons are lost along these field lines while ions are trapped. Then, the positive electric field appears at the plasma edge. That is a key to understand where is the effective plasma boundary. Magnetic topology is an important issue in stellarator and tokamak researches because the 3D boundary has the important role to control the MHD events or detached plasma. Since the LHD can control the width of the stochastic magnetic field by changing the preset vacuum magnetic axis, it is a good platform to study how the radial electric field appears with the different stochastic width. Two magnetic configurations with different widths of the stochastic layer in the vacuum are studied for low-β discharges. It has been found that the positive electric field appeared in the outside of the last closed flux surface. When comparing the vacuum magnetic field, the positions of the positive electric field are observed in the boundary of the stochastic layer and the scrape-off layer. To understand where is the boundary of the stochastic layer and the scrape-off layer, the magnetic field line is analyzed statistically. The variance of the magnetic field lines in the stochastic layer is increased to the outward for both configurations. However, the skewness, which means the asymmetry of the distribution of the magnetic field line, increased for only one configuration. If the skewness is large, the connection length becomes effectively short. Since that is consistent with the experimental observation, the radial electric field can be considered as an index of the magnetic topology.

For stellarators and heliotrons, nested flux surfaces cannot be assumed because three-dimensional (3D) systems do not have symmetry. If a small perturbed field exists, the magnetic field structure becomes easily stochastic. In the Large Helical Device (LHD) [1], the stochastic layer of magnetic field lines in the plasma edge can be expected for the vacuum model [2]. A pair of large helical coils consist of 450 superconducting cables and cross sections of those coils are not simple rectangular. Sophisticated shapes of helical coils make high-order perturbed field, and unstable orbits of the magnetic field are overlapped in the region of strong magnetic shear. In such a case, three layers can be defined in the plasma edge of the LHD. The first layer consists of nested flux surfaces. In the vacuum model, nested flux surfaces are confirmed. The second layer is the stochastic layer where magnetic field lines become stochastic but the connection length of magnetic field lines is very long compared with the electron mean free path. That is a characteristic of the magnetic field structure in the LHD. The last is the scrape off layer (SOL). In the scrape-off layer, the magnetic field line is opened to the divertor and the vessel. From experimental and theoretical studies, it has been found that these sophisticated magnetic field structures affect MHD properties and transport. However, experimental identifications of these three layers, in other words, identifications of the magnetic field structure, are very difficult.

Recently, the radial electric field, E_r, in the plasma edge region is being studied in the LHD experiments [3, 4, 5]. If electrons are lost along the open field lines of the edge magnetic field, a positive E_r might be appeared. This means that the positive E_r or strong E_r shear suggests an effective plasma boundary that is beggning to open magnetic field lines. In previous studies, the effective plasma boundary defined by the positive E_r shear clearly correlates to the change of the magnetic field structure [3]. If the plasma beta value, β, is increased, the effective plasma boundary shifts to the outward of the torus [6, 7]. Comparing 3D MHD equilibiurm calculations, it was found that positions of the boundary defined by the positive E_r shear correlate boundaries between long and short connection lengths of the magnetic field [4]. This is also an important problem in tokamak experiments. The 3D perturbed field is a topic of interest in tokamaks. Usually, the plasma boundary of tokamak plasmas is clearly defined by the separatrix. However, with a superposed resonant magnetic perturbation (RMP), the magnetic field structure becomes stochastic. In such a case, we cannot use the separatrix as the plasma boundary. In addition, the magnetic field structure might be similar to the LHD field, which has three layers as described above. We have a common problem with respect to the plasma boundary in helical devices and tokamaks [8, 9, 10]. Thus, the experimental study of the magnetic field structure in the LHD will help to give answers to the RMP experiment in tokamaks.

However, a difficult task still remains. That is, impacts of the magnetic field structure onto the radial electric field should be considered. In the previous study, clear difference of the E_r shear in two magnetic configurations, which have thin and wide stochastic layer, was found [5]. In this study, we examine more extensively the radial electric field onto the magnetic field structure. To understand the radial electric field in the stochastic field, we study two magnetic configurations which have different stochastic field widths. As discussed above, the radial electric field should be connected from the nested flux surfaces layer to the SOL through the stochastic layer. That means the radial electric field in the SOL can be considered from the SOL physics. Since the electron temperature gradient has an important role on the radial electric field in the SOL [11], we study the correlation of the radial electric field and the electron temperature gradient in the edge region. In this study, we examine the radial electric field in the edge region but the radial electric field in nested flux surface region is outside the scope of this study.

In the LHD device, the vacuum magnetic configuration can be controlled by the preset vacuum axis position, R_{ax}. In figure 1, Poincaré plots of inward and outward shifted configurations are shown for a horizontally elongated cross section. The inward shifted configuration is the standard configuration in the LHD experiment. This cross section corresponds to the cross section of the Thomson scattering and charge exchange recombination diagnostics. Plots are magnified up to $R = 3.5 \sim 4.8$m to focus on the peripheral region. The colors of the dots in the Poincaré plot indicate the connection length of the magnetic field lines, L_C. The L_C is plotted from 10m to 1000m in a logarithmic scale. The preset vacuum magnetic axis position of the inward shifted configuration is 3.6m and that of the outward shifted configuration is 3.9m. In both configurations, clear flux surfaces are seen inside the vacuum LCFS. The outer position of the LCFS for the inward shifted configuration is R=4.55m on the Z=0 line. For the outward shifted configuration, the position of the LCFS is R=4.56m on the Z=0 line. This means the position of the vacuum LCFS is almost the same in both configurations. Outside of the LCFS, open field lines appear and the magnetic field lines become stochastic. In particular, for the outward shifted configuration, the width of the stochastic layer is wider than that of the inward shifted configuration. To see differences for both configurations, contours of the connection length are shown in figure 2. The upper part (Z >0) shows the inward shifted configuration and the bottom part ($Z < 0$) shows the outward shifted configuration. At the region for $R > 4.65$m, opened and closed field lines overlap in the stochastic layer. To understand these characteristics, rotational transform, ι, profiles for both cases are plotted in figure 3. For the inward shifted configuration, the rotational transform on the axis (LCFS) is decreased (increased) compared to the outward shifted configuration. This means the magnetic shear of the inward shifted configuration is stronger than the magnetic shear in the outward shifted configuration. Thus, the width of the stochastic layer is increased for the outward shifted configuration because of weak magnetic shear. Since the stochasticity of the magnetic field in the peripheral region can be controlled for the vacuum field, the LHD is a good platform to study MHD and transport in a stochastic field.

In this study, we examine low-β discharges ($\beta \leq 0.5\%$) in order to focus on the relation between the radial electric field and the magnetic field structure. To do that, some shots are reproduced with the same experimental conditions of the fueling, heating, and other aspects. In figure 4, radial profiles of radial electric field, E_r, and electron temperature, T_e, are shown for the inward and the outward shifted configurations. The figures on the left show cases of the inward shifted configuration and the figures on the right show cases of the outward shifted configuration. Figures in the upper row are E_r profiles and figures in the bottom row show T_e profiles. These profiles are plotted along the $R-$axis in the horizontally elongated cross section corresponding to figure 1. Black arrows in figures indicate a position of the vacuum LCFS on the cross section. We are interested in only the E_r at the ouside of the vacuum LCFS. The radial electric field in the inside of the LCFS is not discussed in this study. For the inward shifted configuration, E_r profiles change from negative values to positive values at $R \sim 4.55$m. That is almost the same position of the vacuum LCFS. And then, the E_r becomes almost zero at $R \sim 4.6$m and maximum at $R \sim 4.65$m. That is close to the boundary of the opened and closed magnetic field lines shown in figure 2. Comparing E_r profiles with T_e profiles, the T_e outside the maximum E_r positions is sufficiently small. That suggests the region with maximum E_r means a boundary of an effective plasma confinement region, where there is a connecting region of the stochastic layer and SOL. On the other hand, for the outward shifted configuration, the E_r changes from the negative value to the positive value at $R \sim 4.58$m, which is slightly outward toward the inward shifted configuration. However, the positive E_r shear is more gradual compared with the inward shifted configuration. The E_r becomes almost zero at $R \sim 4.65$m and the maximum value at $R \sim 4.7$m, but the T_e at $R \gtrsim 4.7$m is still higher than cases of the inward shifted configuration. In figure 1 and figure 2, a boundary between opened and closed magnetic field lines for the outward shifted configuration is the outside of $R = 4.7 \sim 4.75$m. Unfortunately, the range of the CXS diagnostics is limited at $R \lesssim 4.7$m within small errors. Therefore, according to a physical interpretation for the inward shifted configuration based on figure 2, the maximum E_r might appear in the further outward region of $R \sim 4.75$m because the stochastic layer is wider compared with that for the inward shifted configuration.

In a 1D fluid transport model in the SOL region [11], which assume fast parallel transport along opened field lines, the radial electric field E_r can be considered simply related to the T_e gradient as

$$E_r = -\frac{\partial \Phi}{\partial r} \propto \frac{dT_e}{dr}. \tag{1}$$

In figure 5, profiles of E_r and ∇T_e are shown for the inward and outward shifted configuration. To study the T_e gradient, those figures are the function of the effective minor radius, r_{eff} [12]. For the inward shifted configuration, good correlations of E_r and ∇T_e profiles are found. The positive E_r in the plasma edge is about 5 kV/m. The ∇T_e is about -5 keV/m at r_{eff} of $E \sim 0$. The order of both values are the same and those values correspond within small factors. On the other hand, for the outward shifted configuration, the positive E_r is about 3 kV/m and the maximum ∇T_e is about -4.5 keV/m. The order of those values are the same, but the factor is different compared with the inward shifted configuration. In addition, the correlation of E_r and ∇T_e profiles is good but the slope of ∇T_e profiles corresponding to the positive E_r shear shifts to the outward. As was discussed above, if the positive E_r in the plasma edge means the boundary between opened and closed field lines, the maximum E_r might appear around $r_{\text{eff}} \sim 0.6$. In such a case, both results in the inward and outward shifted configuration are consistent. To confirm that hypothesis, we need further studies, especially studies of the E_r in the SOL. That is a future subject, and will be discussed in a separate paper.

To study how magnetic field lines opened from the stochastic layer to the SOL for the inward and outward shifted configuration qualitatively, some statistical quantities are calculated in the vacuum model. In figure 6, profiles of the variance and skewness of magnetic field lines are shown for two configurations. To estimate those values in the stochastic layer, we use the Chaotic coordinate [13]. The variance is increased in the stochastic layer for both configurations. That means the radial deviation of magnetic field lines increases in the stochastic layer. However, the skewness, which means the asymmetry of the distribution function, is different for both configurations. For the inward shifted configuration, the asymmetry of the distribution shifted to the outward appears from $R \sim 4.6$m. On the other hand, for the outward shifted configuration, the skewness is almost zero $R = 4.55 \sim 4.65$m. Outside of R at $R \sim 4.65$m, the strong asymmetry appears. A possible interpretation to explain the magnetic configuration for the inward and outward shifted configurations is shown in figure 7. For the inward shifted configuration, since the asymmetry of the magnetic field line distribution appears at $R \sim 4.6$m, unstable orbits of stochastic field lines intersect many times between long and short L_{C} in the stochastic layer. It might be considered that the effective L_{C} becomes short from the viewpoint of the parallel electron transport. For the outward shifted configuration, orbits of magnetic field lines in the stochastic region are unstable but the distribution of magnetic field lines is symmetric. At $R = 4.55 \sim 4.65$m, magnetic field lines do not intersect between long and short L_{C}, and the effective L_{C} might be long compared with the inward shifted configuration. The maximum E_r will appear in the outside of $R \sim 4.7$m. That is consistent with the experimental observation.

In summary, we have studied the radial electric field, E_r, to consider its impact onto the magnetic field structure. Since the LHD device can control the width of the stochastic layer of the vacuum field, two magnetic configurations with different widths of the stochastic layer, which are the inward and outward shifted shifted configuration respectively, are studied. To study only the effect of the magnetic configuration on the E_r, low-β discharges are studied. In those discharges, no significant fluctuations of MHD events are observed. For the inward shifted configuration, which has the thin stochastic layer, the positive E_r appears outside of the vacuum LCFS and the T_e is sufficiently small there. On the other hand, for the outward shifted configuration, which has the wider stochastic layer, the positive E_r also appears in the outside of the vacuum LCFS but the T_e is still high compared with the inward shifted configuration. To study how the E_r appears in the stochastic region, the correlation of the radial electric field, E_r, and the gradient of the electron temperature, ∇T_e, is studied for both configurations. In both configurations, good correlations are found, but the ∇T_e profile for the outward shifted configuration is shifted to the outward. To understand this difference, the distribution of magnetic field lines are studied statistically in both configurations. For the inward shifted configuration, that the asymmetry of the magnetic field line distribution shifted to the outward appears in the outside of the vacuum LCFS, and that corresponds to the effective connection length, L_{C}, becoming short in the stochastic layer. However, although the stochastic layer for the outward shifted configuration is wider than that for the inward shifted configuration, the effective L_{C} for the outward shifted configuration is longer than that of the inward shifted configuration. That is consistent with the ∇T_e becoming small at $R \gtrsim 4.7$m. Therefore, the positive E_r might be maximum at $R \gtrsim 4.7$m. From this study, the radial electric field profile reflects onto the magnetic configuration. However, it is still open question how the radial electric field in the nested flux surface region and SOL are connected through the stochastic layer. To understand that, we need further studies of the radial electric field in the edge region, especially in the SOL. However, the measurement of the radial electric field in the SOL is very difficult and the error is very large. Careful and systematic analyses should be conducted. That is a future subject and will be discussed in a future paper.

Acknowledgments

This work is performed with the support and under the auspices of the NIFS Collaborative Research Program NIFS07KLPH004 and NIFS10KLPH006. This work was supported by Grant-in-aid for Scientific Research (C) 25420890 from the Japan Society for the Promotion of Science (JSPS).

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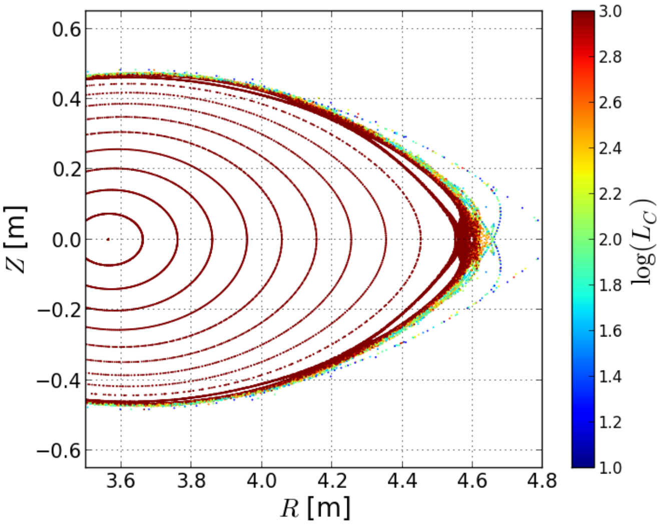
(a) Inward shifted configuration ($R_{\rm ax}$=3.6m)



(b) Outward shifted configuration ($R_{\rm ax}$=3.9m)

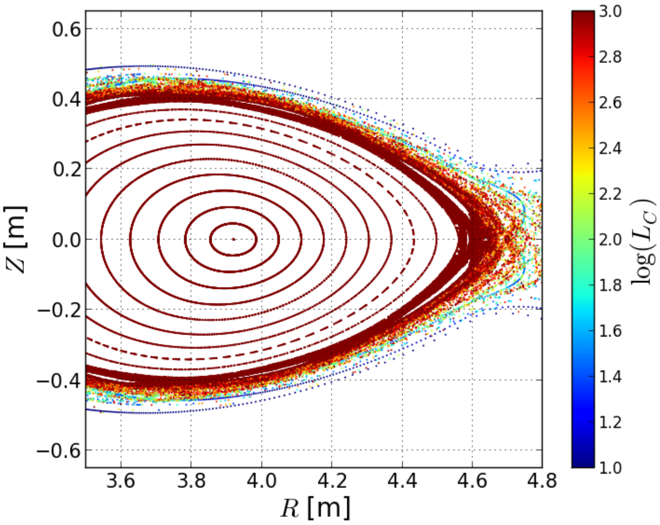


Figure 1. Poincaré plots for (a) inward and (b) outward shifted configurations are plotted for a horizontally elongated cross section ($\phi = \pi/M$). Colors indicate the logarithm of the connection length of magnetic field lines.

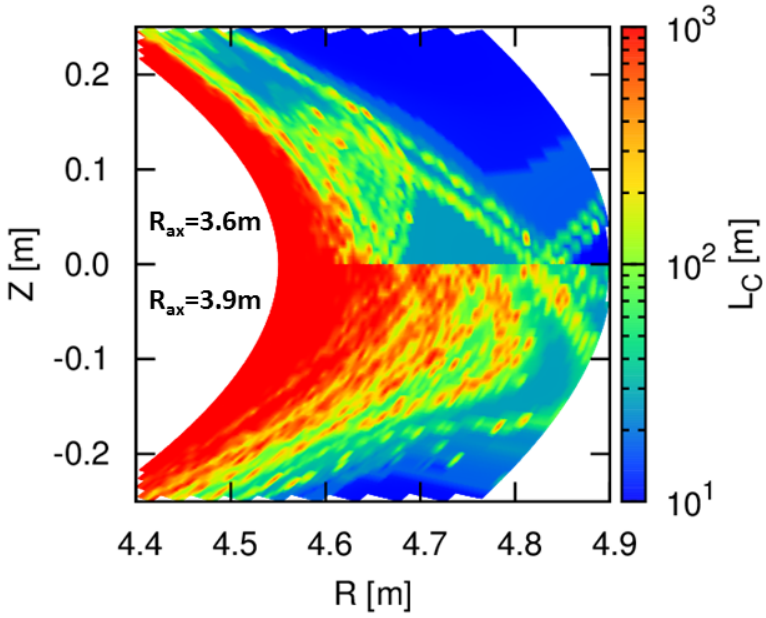


Figure 2. A comparison of the connection length of magnetic field lines is shown for inward ($Z > 0$ m) and outward ($Z < 0$ m) shifted configurations. Colors indicate the logarithm of the connection length of magnetic field lines.

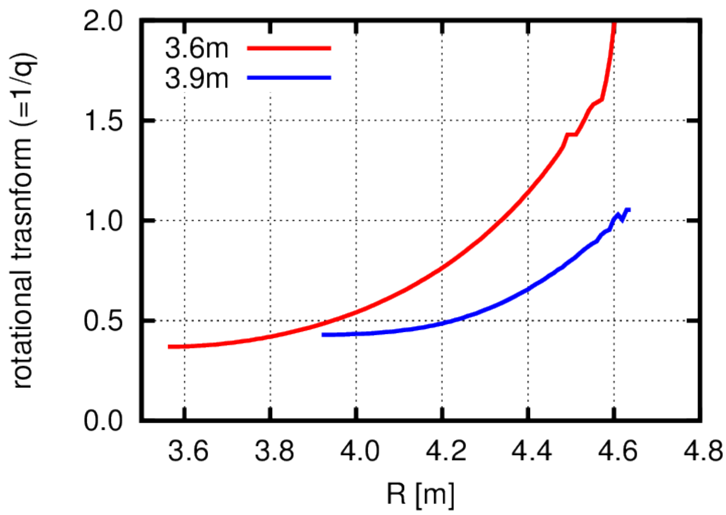


Figure 3. A comparison of the rotational transform is shown for inward (red) and outward (blue) shifted configurations.

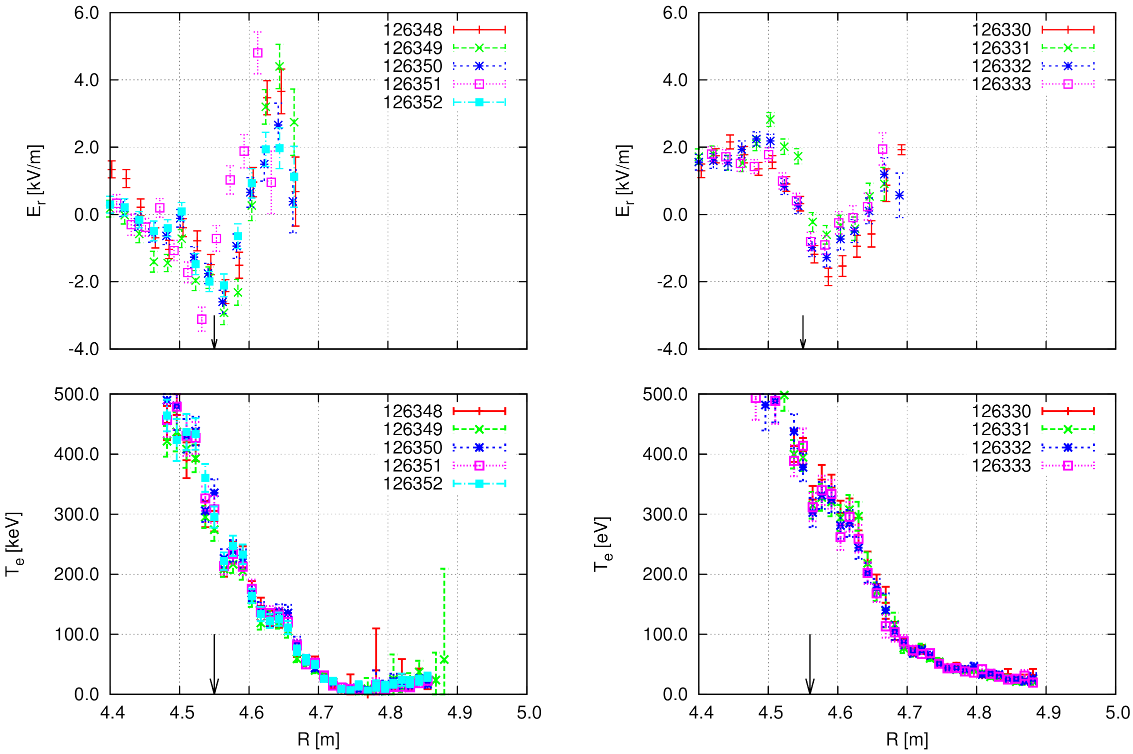


Figure 4. Profiles of the radial electric field (top) and electron temperature (bottom) for the inward (left) and outward shifted (right) configurations are shown as a function of R, respectively. The black arrow indicates the position of the vacuum LCFS.

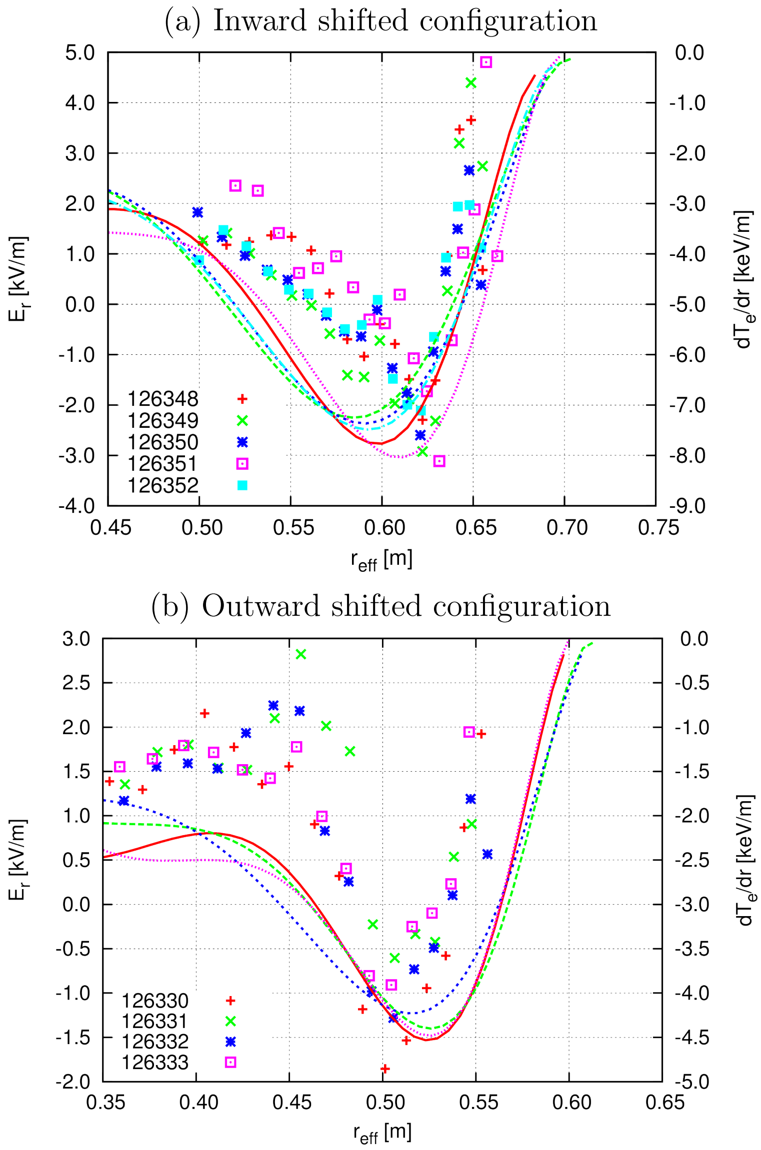


Figure 5. Comparisons of the radial electric field and gradients of the electron temperature, ∇T_e, shown for (a) inward and (b) outward shifted configurations. Symbols indicate the E_r and lines indicate ∇T_e.

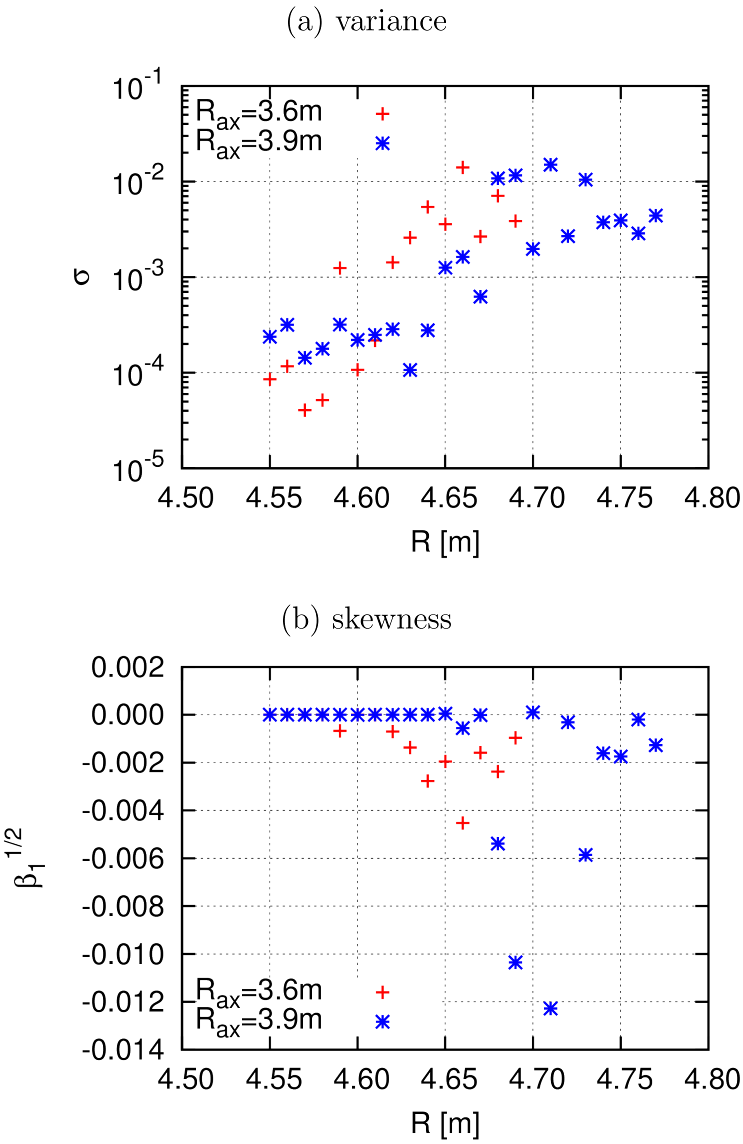


Figure 6. The variance and skewness of magnetic field lines are shown as a function of R. The inward and outward shifted configurations are compared.

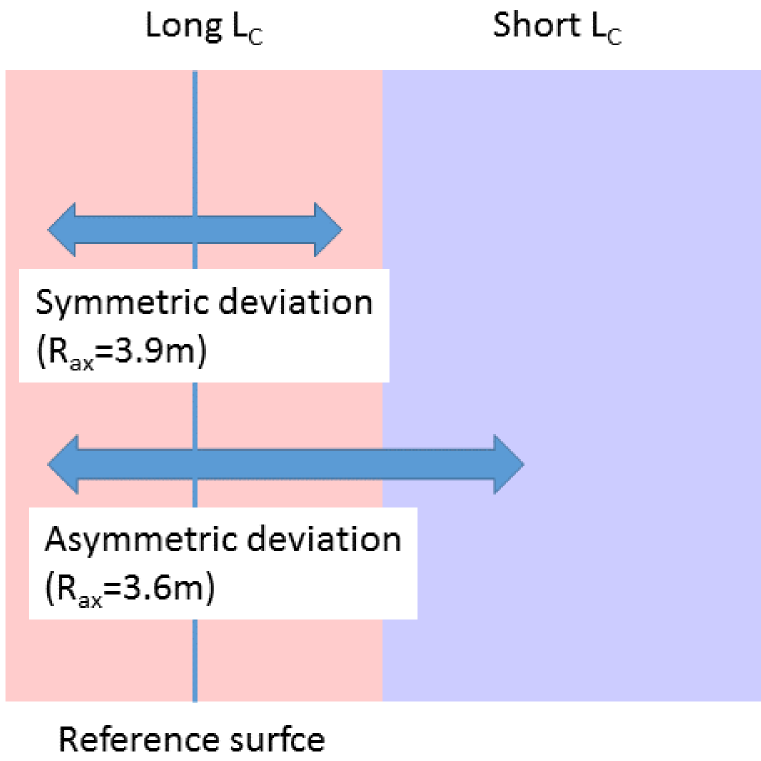


Figure 7. An interpretation of different diffusion properties for the inward and outward shifted configuration is shown as a schematic view.